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Planning the most suitable travel speed for high frequency railway lines

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Abstract

This paper presents a new method to calculate the most suitable travel speed for high frequency railway lines to achieve as much capacity as possible for congested railway lines. The method calculates the most suitable travel speed based on the braking distance and information about the interlocking system. Based on the braking distance it is possible to calculate the minimum headway time, and thereby determine the buffer time when knowing the frequency. Hence the headway time can be divided into minimum headway time and buffer time.

The buffer time is an indicator for the spare capacity of the railway line, and the more buffer time on the railway line, the better punctuality and the better possibilities to run more trains. Based on the described method a case example from the suburban railway lines of Copenhagen will be shown. The case example shows that a reduction of the maximum travel speed by 6% in central Copenhagen can increase the capacity by 11%. The increased capacity will improve the punctuality of the trains in central Copenhagen – even though some of the capacity will be used to run more trains through Copenhagen.

Keywords

Capacity, Headway, Buffer time, Simulation, Punctuality

1 Introduction

High frequency railway lines often suffer from lack of capacity. These problems can traditionally be solved by improving the infrastructure or bundle the trains for better utilization of the capacity. The capacity of high frequency railway lines depends on the minimum headway time of the trains.

Calculations of headway times in rail systems in Scandinavia and in many OR-papers are often assumed independent of the travel speed. Normally, this assumption is reasonable, but sometimes there is a big difference in the headway time as a result of a slight change in the travel speed. The big change in the headway time can be explained by the structure of the signal system with discrete block sections, which can affect the travel speed.

A train has to be able to stop before a restrictive signal. This means that the braking distance on a railway line with discrete block sections has to be smaller than or equal to

the summarized length of free block sections and a safety distance. A change in the travel speed changes the braking distance. Even a slight change in the braking distance can affect the headway distance considerably, if an extra block section is needed to ensure that the train is able to stop before a signal. In that way, the headway time can not always be assumed independent of the travel speed.

Changes in the travel speed will not only affect the minimum headway time, but also the buffer time between the trains in the timetable due to a higher minimum headway time which will result in less buffer time. The buffer time ensures that a small delay of one train is not propagated to the following trains. Less buffer time increases the risk of propagation of delays.

If the minimum headway time is getting larger than the planned or possible headway time (e.g. because of higher speed due to delays), the train will have to reduce its travel speed. Therefore, it is important to be able to plan the most suitable travel speed, especially for high frequency railway lines.

Normally, the lengths of the block sections of the railway line are adapted to the travel speed of the most common train type and speed of the rail line. This gives the disadvantage that some trains might use too much capacity because of their train characteristics. Over time the trains will also be replaced by new trains or the infrastructure will be upgraded, which can cause a higher utilization of the capacity, hence the block lengths are not adapted to the new situation. This paper suggests a new method to change/optimize the travel speed to fit the block lengths of the infrastructure. This makes it possible to gain more capacity on a railway line.

1.1 Paper objective

This paper presents a new method to optimize the travel speed of trains, so that a better utilization of the capacity can be achieved. The extra capacity achieved can be used for fewer delays and better punctuality, more routes, or a combination of both. Furthermore, the paper will test the method on a real case example from Copenhagen.

1.2 Paper outline

The next section briefly describes the definitions and notations used in the following. Section 3 describes the method to calculate the most suitable travel speed step-by-step, starting with calculating the braking distance and then the travel speed of trains for both discrete and continuous signalling systems. This provides the background for calculating the most suitable travel speed and the effects of deviations from the most suitable travel speed.

Using the method developed in section 3, section 4 describes a case example of improved capacity on the suburban railways of Copenhagen. Here the capacity will be examined for scenarios with different travel speeds and different lengths of block sections. The scenarios will be simulated in RailSys in order to carry out an evaluation.

Against the background of section 3 and 4, section 5 concludes on the method and describes the perspectives.

2 Definitions and Notation

This paper uses terminology usually used in the railway literature. However, since the terminology differs from country to country, an overview of the terminology used in this paper is provided in table 1.

Table 1: Short description of terminology

Term	Explanation
ATC	Automatic Train Control (ATC) is a safety system ensuring a train to stop before a restrictive (red) signal
Block section	The length of track between two block signals, cab signals, or both
Block occupation time	The time a block section is occupied by a train
Braking percentage	The ratio of the braking force to total vehicle weight. The braking percentage expresses the braking force required for braking 1 ton
Buffer time	The time difference between actual headway and minimum allowable headway
Delay	The average delay of the trains
Headway distance	The distance between the front ends of two consecutive trains moving along the same track in the same direction. The minimum headway distance is the shortest possible distance at a certain travel speed allowed by the signalling and/or safety system
Headway time	The time interval between two trains or the (time) spacing of trains or the time interval between the passing of the front ends of two consecutive vehicles or trains moving along the same lane or track in the same direction
Punctuality	The part of trains arriving less than X minutes late
Running time supplement	The difference between the planned running time and the minimum running time
Travel speed	The speed of the train at a certain time

The terms described in table 1 is further illustrated figure 1

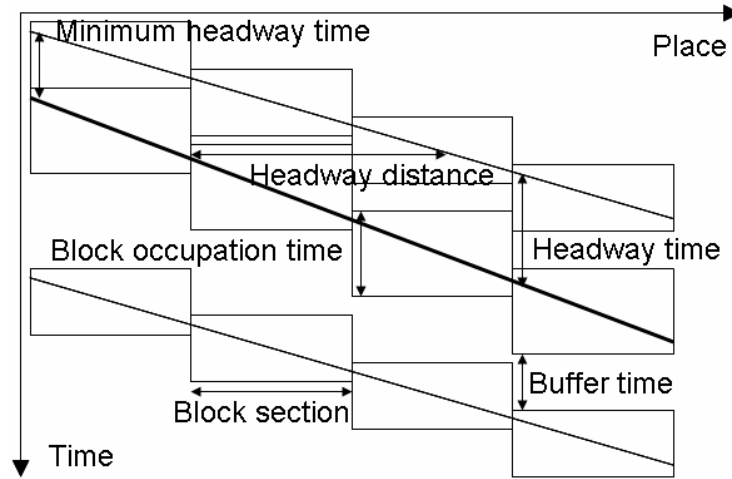


Figure 1: Time definitions

The notation in the paper will be as seen in table 2.

Table 2: Notation

Explanation	Symbol	Unit
Braking retardation	a_r	m/s^2
Length of first block section behind train 1	B_1	m
Length of block section j behind train 1	B_j	m
Breaking percentage	λ	
Braking ratio	c	
Acceleration of gravity	g	m/s^2
Gradient	i	
Length of train 1	L	m
Braking distance	S_b	m
Optimal braking distance	$S_{b,opt}$	m
Headway distance	S_h	m
Safety distance behind a signal	S_s	m
The time it takes to achieve full braking force	t_b	s
Buffer time	t_{bt}	s
Headway time	t_h	s
Minimum headway time	$t_{h,min}$	s
Reaction time of the engine driver	t_r	s
Reaction time of the brakes	t_s	s
Total reaction time of brakes for calculation of braking distance ($t_r + t_s + \frac{1}{2}t_b$)	t_R	s
Velocity/travel speed	v	m/s
The optimal velocity/travel speed	v_{opt}	m/s

3 Method

This section describes how to calculate the braking distance for trains. The braking distance is a crucial parameter to calculate the possible travel speed for a train on a certain railway line. Knowing the braking distance and the possible travel speed it is possible to determine the most suitable travel speed using the new method described in this section. Furthermore, this section will describe the consequences of deviations from the most suitable travel speed.

3.1 Calculation of Braking Distance

To be able to calculate the most suitable speed to minimize the block occupation time, it is necessary to know the possible braking distance at the current line section. In simple mechanics, it is possible to calculate the braking distance (S_b) as a function of the speed (v) when the braking starts and the braking retardation (a_r) of the train,

$$S_b = \frac{v^2}{2 \cdot a_r}. \quad (1)$$

The braking retardation (a_r) can be calculated in various ways. In Denmark, the empiric Mindener formula is normally used [3] and [7],

$$a_r = 0.061 \cdot \left(1 + \frac{\lambda}{10}\right) = \frac{6.1 \cdot \lambda + 61}{1000}. \quad (2)$$

λ describes the braking percentage defined as the ratio of the braking force to total vehicle weight and expressing the braking force required for braking 1 t. λ has different values for various types of brakes and rolling stock and is normally found experimentally. Because equation (2) is empiric and λ is found by experiments, the formula takes all kinds of retardations including air resistance into account [7]. In this paper the wind speed will be neglected. Trains with anti-lock brakes are not allowed to obtain a larger braking distance than 20% more than trains without anti-lock brakes according to approval by the International union of railways (UIC). Therefore, the equation (2) is rectified by 20% [7],

$$a_r = \frac{6.1 \cdot \lambda + 61}{1000} \cdot \frac{100}{120} = \frac{6.1 \cdot \lambda + 61}{1200}. \quad (3)$$

The influence of the gradient (i) can be found from the simple mechanics as an extension of the braking retardation. The extension of the braking retardation can for small gradients be assumed equivalent to the product of the acceleration of gravity (g) and the gradient (i) in percent and negative at falls. Under normal circumstances trains do not brake sharply, but only with a certain braking ratio (c). For instance the braking ratio for the Danish ATC system is 0.6 for train units and 0.7 for all other kinds of trains. Taking the braking ratio and the gradient into account the braking retardation of the train will be,

$$a_r = c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i. \quad (4)$$

Combining the equations (1) and (4) it is possible to calculate the braking distance for trains without taking the reaction time of either the engine driver or the braking system into account,

$$S_b = \frac{v^2}{2 \cdot \left(c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i \right)}. \quad (5)$$

The reaction time can be divided into the reaction time of the engine driver (t_r) and the reaction time of the brakes (t_s). The reaction time of the brakes can be further divided into the reaction time from the brakes are applied to the brakes start braking the train (t_s), and the time it takes from the train starts braking, until the brakes of the whole train are working with full braking force (t_b). Depending on the type of brakes, the reaction times of the brakes can have a large variation.

The reaction time of the engine driver (t_r), and the time from the brakes are applied to the brakes start braking the train (t_s) extends the braking distance proportionally with the speed. The time it takes from the brakes start working before all brakes work with full braking force (t_b) depends on the type of braking system. It can, however, be assumed that the braking force will increase linearly as described in Tilli [7] and Andersson and Berg

[1]. This gives the braking distance as,

$$S_b = \frac{v^2}{2 \cdot \left(c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i \right)} + (t_r + t_s + \frac{1}{2} \cdot t_b) \cdot v. \quad (6)$$

The braking distance has been seen calculated in various ways differing from the expression in equation (6). A short overview of different formulas for calculating the braking distance can be found in e.g. Profillidis [5] and also Barney, Haley and Nikandros [2]. In this paper it is, however, chosen to use the expression in equation (6) while it is a commonly used empiric formula, and no better formulations are known used internationally by the authors. Other ways of calculating the braking distance can also be used for the further calculations in the method described in this paper.

3.2 Calculation of Travel Speed

To be able to calculate possible travel speeds for trains, it is necessary to know the allowed braking distance of the train. The possible travel speed (v) will according to equation (6) be,

$$v \leq a_r \cdot \left(-t_R \pm \sqrt{t_R^2 + \frac{2 \cdot S_b}{a_r}} \right)$$

Where :

$$t_R = t_r + t_s + \frac{1}{2} \cdot t_b$$

$$a_r = c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i$$
(7)

When calculating the possible travel speeds for trains using equation (7), only the positive value of the term in the square root is used.

The allowed braking distance is determined by the signal system of the railway line. If there is a moving block system on the line, the maximum allowed braking distance is the actual braking distance of the train plus a safety distance. Moving block systems are still not common and not existing in Denmark. Instead traditional discrete block systems are used and on the main lines supplied with either continuous or discrete ATC (with or without wiggly wire) and on the Copenhagen suburban railway lines the HKT (speed control and train stop) system, which is similar to the continuous ATC system.

Discrete ATC

The Danish ATC system is, from the point of origin, based on discrete blocks where the ATC information is only updated at balises placed close to the signals – a so-called discrete ATC system. The Danish discrete ATC system is in many ways similar to the German PZB (Punkt Zug Beeinflussung) system. The headway distance (S_h) for the discrete ATC system can be measured as the sum of block sections within the braking distance (S_b) of a train and an extra block section, a safety distance (S_s) after the red signal and the length of the train in front (L), as shown in figure 2.

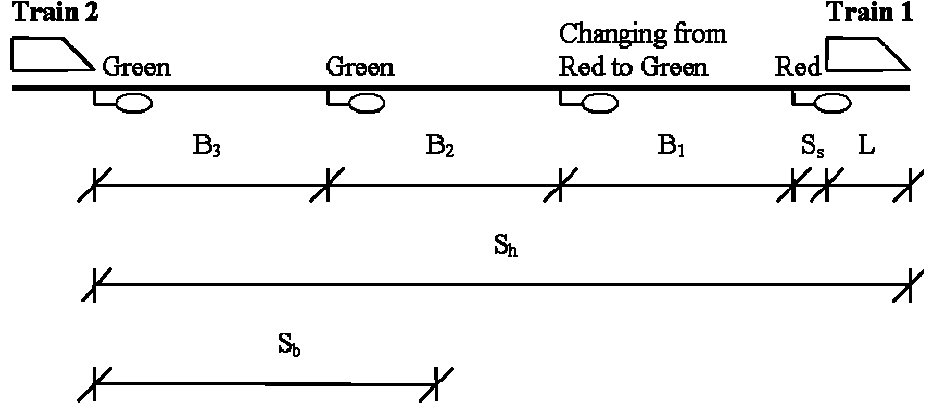


Figure 2: Discrete blocks and discrete ATC

The headway distance can then be expressed as,

$$S_h \geq \sum_{j=1}^n B_j + S_s + L. \quad (8)$$

The sum of B_j 's describes the number of block sections in the braking distance plus an extra block section. The braking distance can be expressed as,

$$S_b \leq \sum_{j=2}^n B_j. \quad (9)$$

Besides the expression in equation (9), the braking distance depends on the ATC system. At present, the Danish ATC system can only look 2 or 3 block sections ahead, which limits the travel speed, hence the speed depends on the allowed braking distance. The future ETCS (European Train Control System) will be able to look more than 3 block sections ahead.

Continuous ATC and HKT

Line sections with a high rate of capacity utilization can be equipped with wiggly wire so that a continuous ATC system is achieved. The wiggly wire system is, as described in Kaas [4], expensive to establish and should therefore only be established at railway lines with a high rate of utilization or at bottlenecks. The wiggly wire makes it possible to update the ATC system along the line instead of only at balises. This gives the advantage of being able to speed up the train when a block section ahead becomes free, which improves the capacity.

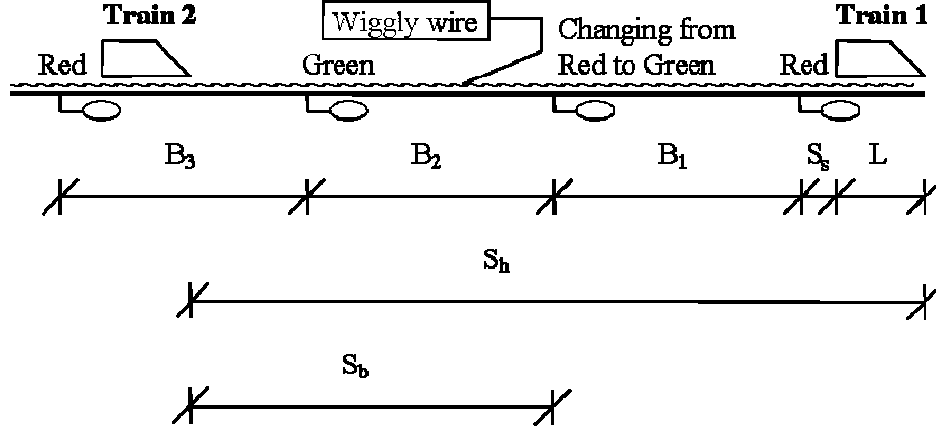


Figure 3: Discrete blocks and continuous ATC

Since the wiggly wire can update the ATC system at all times, the headway distance will be smaller than for a discrete ATC system. The headway distance can be expressed as,

$$S_h \geq S_b + B_1 + S_s + L. \quad (10)$$

The braking distance can be expressed as in equation (6). If the braking distance is equal to the length of a whole number of block sections, the headway distances calculated in equations (8) and (10) are exactly alike.

Like the Danish discrete ATC system, the Danish continuous ATC system can only look 2 or 3 block sections ahead. The future ETCS system can however look further ahead.

On the suburban railway lines in Copenhagen, the HKT system is used. The HKT system is similar to the continuous ATC system. The HKT system can, however, look more than 3 block sections ahead, but the HKT system can only be programmed for up to 4 different speed limits depending on the number of free block sections ahead.

3.3 Calculating the most Suitable Travel Speed

The most suitable travel speed can be defined in different ways. For the passengers, the most suitable travel speed is achieved when the total travel time (including waiting times etc.) is as short as possible. For a congested railway line, the most suitable travel speed is when the headway time is as short as possible because it results in the highest possible capacity. For the railway company, the most suitable travel speed will be a mix of the most suitable travel speed for the passengers and the shortest headway time on the congested railway line/lines.

The headway time (t_h) depends on the headway distance (see equations (8) and (10)) and the block occupation time, which is equivalent to the travel speed of the train is,

$$t_h = \frac{S_h}{v}. \quad (11)$$

The difference in the minimum headway distance between the discrete and the continuous ATC system can be seen in figure 4.

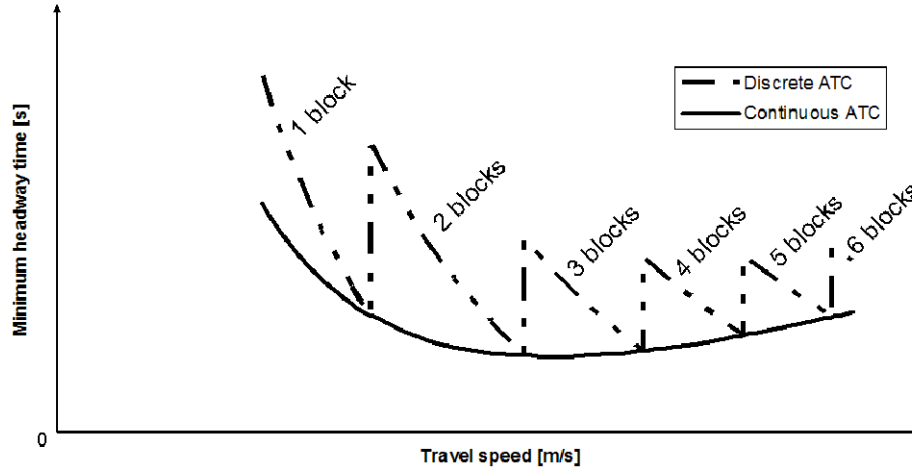


Figure 4: Minimum headway time as a function of the travel speed and the block sections in the minimum headway distance

Figure 4 is a conceptual figure showing that the minimum headway time in the discrete ATC system in the best case is equal to the headway time for the continuous ATC system. The headway time is the same, hence equations (8) and (10) are equivalent when the length of the braking distance has exactly the same length as a whole number of block sections.

The optimal travel speed is when the minimum headway time is as short as possible. When the travel speed is below the optimal travel speed the minimum headway time can be reduced by speeding up since the block occupation time is too long. At travel speeds above the optimal travel speed, the braking distance has become too long, so that the block sections are reserved for too long time. It is not possible to have travel speeds which require looking more block sections ahead than the ATC system allows.

As earlier mentioned, there are numerous formulas for calculating the braking distance, see Profillidis [5] and Barney, Haley and Nikarandos [2] for some other formulas. Common to all the formulas is the shape of the lines in figure 4. This indicates that the methods of calculating the headway time are the same and only the parameters vary.

For the continuous ATC system, the travel speed giving the shortest headway time can be found as the global minimum. The global minimum can, since it is a continuous function, easily be found by an ordinary differential equation,

$$\begin{aligned}
t_{h,\min} &= \frac{S_b + B_1 + S_s + L}{v} \\
t_{h,\min} &= \frac{\frac{v^2}{2 \cdot \left(c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i \right)} + (t_r + t_s + \frac{1}{2} \cdot t_b) \cdot v + B_1 + S_s + L}{v} \cdot \frac{\partial v}{\partial t_{h,\min}} \\
&\quad \Downarrow \\
t'_{h,\min} &= \frac{1}{2 \cdot \left(c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i \right)} - \frac{B_1 + S_s + L}{v^2} = 0 \\
&\quad \Downarrow \\
v_{\text{opt}} &= \sqrt{2 \cdot \left(c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i \right) \cdot B_1 + S_s + L}
\end{aligned} \tag{12}$$

Equation (12) is a continuous function which means that a slight change in the optimal speed will not have a significant impact on the minimum headway time, see figure 4. Therefore, it is often seen that other factors than the minimum headway distance or minimum headway time and thereby the capacity often will be the determining factor for choosing the travel speed.

For railway lines with a discrete ATC system (or without any ATC system), the travel speed has a greater impact on the minimum headway distance than when having a continuous ATC system (cf. figure 4). Even a slight increase in the travel speed can cause a much longer minimum headway time, hence the braking distance occupies an extra block section. When the braking distance (still) is inside the span of a block section, the minimum headway time will decrease with increased travel speed. The optimal travel speed then occurs, when the minimum headway time for the discrete ATC system is close to the minimum headway time achieved with the continuous ATC system.

The local minima with the discrete ATC system can be found by setting the braking distance equal to the length of a whole number of block sections,

$$S_{b,\text{opt}} = \sum_{j=2}^n B_j \tag{13}$$

Equation (13) combined with equations (8) and (11) results in local minimum headway times which can be described as,

$$t_{h,\min} = \frac{\sum_{j=2}^n B_j + B_1 + S_s + L}{v}$$

Where :

$$\sum_{j=2}^n B_j = S_{b,\text{opt}} = \frac{v^2}{2 \cdot \left(c \cdot \frac{6.1 \cdot \lambda + 61}{1200} + g \cdot i \right)} + (t_r + t_s + \frac{1}{2} \cdot t_b) \cdot v$$

The possibility of looking more than 2 to 4 block sections ahead reduces the possibility of optimizing the travel speed, hence it will not be possible to speed up in case of delays. Therefore, the planned optimal travel speed is often lower than the speed calculated in equation (14).

Deviations from the Most Suitable Travel Speed

The method for calculating the most suitable travel speed also provides the possibility of calculating the consequences of deviations from the most suitable travel speed. Knowing the planned headway time between two subsequent trains and the realized headway time at different travel speeds, also the buffer times are known for different travel speeds, hence the headway time can be divided into minimum headway time and buffer time,

$$t_h = t_{h,\min} + t_{bt} \quad (15)$$

Information about the minimum headway time and the planned headway time for a congested or high frequency railway line can be seen on figure 5.

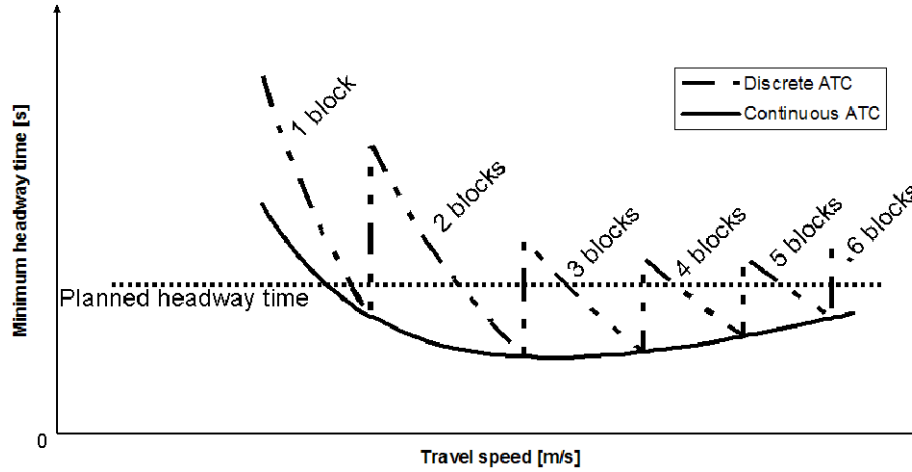


Figure 5: Minimum headway time as function of the speed and the planned headway time

The information in figure 5 shows that it is possible to run the train at (almost) all speeds if the railway line is equipped with continuous ATC. If the railway line is only equipped with a discrete ATC system it is not possible to run the train at certain travel speeds, hence the minimum headway time is longer than the planned headway time. This can also be seen by examining the buffer time of the train, since it is not possible to run a train with a negative buffer time as seen in figure 6.

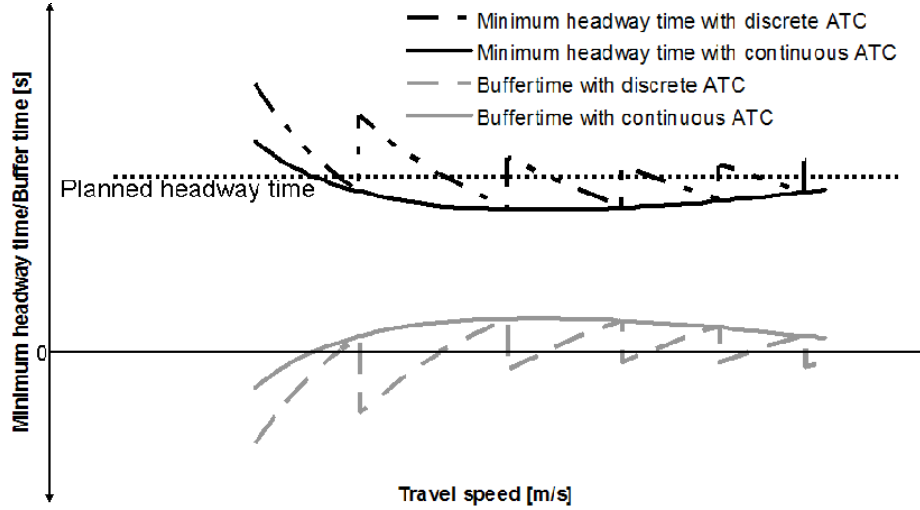


Figure 6: Minimum headway time and buffer time as function of the travel speed

4 Results

The previous section described how to calculate the braking distance. Using the braking distance and information about the infrastructure (block lengths and signalling system), it is possible to calculate the travel speed giving the shortest minimum headway time. The shortest possible minimum headway time gives more buffer time, and by that more capacity, which can be used for running more trains, achieve a better punctuality, or a combination of both.

The calculated optimal travel speed will not necessarily be the best travel speed in practice since the possibility of catching up delays or ensure a short travel time are also important factors.

In the following a case example from the suburban railways of Copenhagen will be presented. In the case example, it will be shown how the method described in this paper can be used to achieve more capacity and a better punctuality on a congested railway line. In the case example present safety procedures and block lengths of the suburban railways of Copenhagen are taken into account.

4.1 A case example

The Copenhagen S-train system suffers from lack of capacity since all the lines, except from the cross line, use the same railway line through central Copenhagen, as shown in figure 7. In the morning peek hour, 10 S-train routes run through central Copenhagen

using a scheduled service in which trains operate at equal and fixed time intervals of 20 minutes.

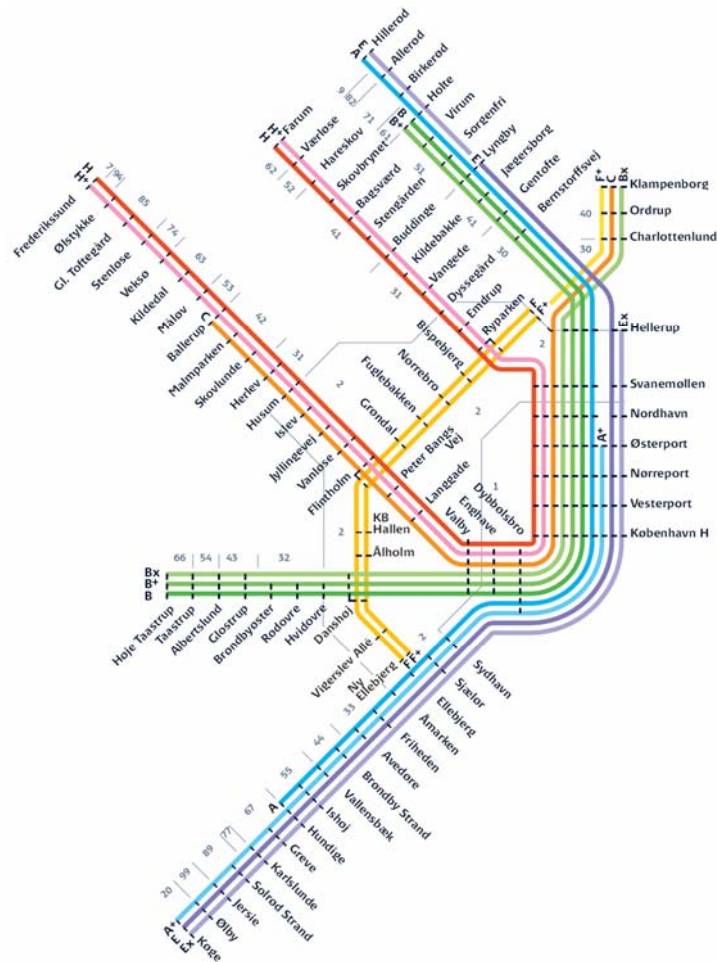


Figure 7: The Copenhagen S-train system year 2005

Due to the intense traffic in central Copenhagen with trains every second minute in the morning peak hours, even small delays are easily spread to the whole system. In the future it is expected that more routes will run through Copenhagen. To run any more trains through Copenhagen with a satisfactory delay distribution it is necessary to increase the capacity.

The most congested part of the railway line in Copenhagen is an approximately 3 km long section from the central station (København H) to Østerport via Vesterport and Nørreport (cf. figure 7). Today, both new and old trains are running on the railway line. Per January 2006, only new trains will be running on the line. When all trains on railway line are new it will be possible to optimize the travel speed according to the block sections to achieve more capacity. Today, the maximum travel speed between the central station

and Østerport is 80 km/h which (with the current block sections) results in a minimum headway time of 114 seconds. By reducing the maximum travel speed to 60 km/h it is possible to reduce the minimum headway time to 101 seconds, see table 3.

Table 3: Optimization of travel speed on the suburban railway line in central Copenhagen

Maximum travel speed	Minimum headway time	Minimum running time
80 km/h	114 seconds	297 seconds
60 km/h	101 seconds	315 seconds

As shown in table 3, it is possible to reduce the minimum headway time by 13 seconds or about 11% just by reducing the travel speed about 6% on a congested railway line. The reduced minimum headway time results in more capacity which can be used for fewer delays and better punctuality, more routes, or a combination of both. If a further decrease in the minimum headway time is requested it is necessary to change the length of the existing block sections. Changing the length of the existing block sections can reduce the minimum headway time by an extra 8-9 seconds, as shown in table 4.

Table 4: Optimization of block sections on the S-train line in central Copenhagen

Scenario	Minimum headway time (theoretically)
Old S-trains, existing block lengths	116 seconds north bound
	114 seconds south bound
New S-trains, existing block lengths	102 seconds north bound
	101 seconds south bound
New S-trains, improved block lengths	93 seconds north bound
	93 seconds south bound

Further improvement of the minimum headway time is not possible, unless changes in the present security procedures are accepted.

Simulation of the changes

To evaluate the effects of reducing the travel speed a simulation in RailSys has been carried out. In the simulations only the section between the central station (København H) and Østerport has been evaluated. 85% of the trains have been inducted initial entry delays of 0-2 minutes (equally distributed) and the remaining 15% of the trains have been inducted initial entry delays of 2-5 minutes (equally distributed) at København H and Østerport. The results of the different scenarios are shown in table 5.

Table 5: Average delay and punctuality (less than 2½ minutes delayed) at different combinations of infrastructure/train types and number of train routes

Scenario	10 trains per 20 minutes	11 trains per 20 minutes	12 trains per 20 minutes	Minimum running time
Old S-trains, existing block lengths	74 sec./65%	NOT POSSIBLE	NOT POSSIBLE	297 seconds
New S-trains, existing block lengths	21 sec./91%	24 sec./89%	NOT POSSIBLE	315 seconds
New S-trains, improved block lengths	20 sec./91%	23 sec./89%	27 sec./88%	315 seconds

The punctuality increases, hence more buffer time or capacity is achieved. The increased capacity, or buffer time, can be used to run even more train routes through Copenhagen. Even though more train routes are running through Copenhagen, the simulations show that the delays and punctuality will improve compared with the situation of today, see table 5.

The results of the simulation in table 5 show that an optimization of the travel speed can improve the capacity of a congested railway line considerably. Changing the travel speed is therefore a cheap way to improve the capacity of a bottleneck. The extra capacity can be used to run more trains, improve the delays and punctuality or a mix of both.

5 Conclusions and Perspectives

This paper has described how to calculate the braking distance using the standard Mindener formula. Having knowledge about different signalling systems, safety systems, and the length of the block sections, it is possible to use the developed method to calculate the most suitable travel speed for a high frequency railway line.

The paper has shown that even slight changes in the travel speed can have a large impact on the capacity at railway lines with a discrete ATC system. The large impact on the capacity is due to large changes in the minimum headway time; hence the braking distance requires an extra block section to be able to brake before a restrictive (red) signal. Contrary to the discrete ATC system, slight changes in the travel speed with continuous ATC system or HKT system do not have equally large impacts on the headway time and the capacity. Therefore, high frequency railway lines and bottlenecks on the infrastructure should have a wiggly wire and a continuous ATC system to improve the capacity.

Changing the maximum travel speed on a congested railway line can have a big impact on the capacity. The capacity can also be improved even though the railway line is equipped with wiggly wire and a signalling system similar to a continuous ATC system. The paper has shown that extending the travel time by 6% on a small section of the suburban railways of Copenhagen, which has a HKT system similar to the continuous ATC, the minimum headway time can be reduced by about 11% in central Copenhagen. By upgrading the signalling system it is possible to improve the minimum headway time by another 9%. Changing the travel speed on a railway line in central Copenhagen, which acts as a bottleneck for the entire suburban railways of Copenhagen, it is possible to run more trains or improve the delays and punctuality for the entire suburban railways.

The developed method of optimizing the travel speed to the block lengths has through simulations shown to be a powerful tool to gain as much capacity as possible on an existing railway line. The simulations have furthermore shown that it is possible to run more trains with a better punctuality when the travel speed is adjusted to the block lengths. Simulations are a difficult way of examining the effects of changes in the travel speed, an easier way to evaluate the effects on the capacity is to use the method described in the UIC capacity leaflet [8].

In the future the developed method can be used on railway lines which are bottlenecks in the railway system. This can be done by changing the running time supplements in the timetable, so that some of the time supplements reallocate between the open line and the stations, which has been described in Rudolph [6].

With a further development and implementation of the method it will be possible to use the method in the planning of timetables. The method can be used to plan the most suitable travel speed for the trains, and in this way be used to calculate the optimal running time supplements for the railway line or the specific train.

In order to improve the described method to calculate optimal running time supplements a stochastic element is required to determine the probability distribution of delays. Having this stochastic element imbedded in the method it will be possible to calculate the optimal combination of travel speed, running time supplements, and buffer times. In this way the average delay and punctuality of the railway system can be improved, but it requires the right stochastic description of the risk of delays, as described in Vromans [9].

References

- [1] Andersson, E., Berg, M. *Railway systems and rolling stock*, Vol. 2, Kungl Tekniska Högskolan, Stockholm, 1999 (in Swedish)
- [2] Barney, D., Haley, D., Nikandros, G., *Calculating Train Braking Distance*, Conferences in Research and Practice in Information Technology, vol. 3, 2001
- [3] Kaas, A.H., *Methods for calculating capacity on railway lines*, Technical University of Denmark, 1998 (in Danish)
- [4] Kaas, A.H., "Optimization of block sections on railways with ATC-systems", In: Lohmann-Hansen, A. (ed.), *Trafikdage på AUC '95*, pp. 185-192, Transportrådet, Aalborg, 1995 (in Danish)
- [5] Profillidis, V.A., *Railway Engineering*, pp. 231-234, Section of Transportation Democritus Thrace University Greece, Avebury Technical, Aldershot, 1995
- [6] Rudolph, R., *Entwicklung von Strategien zur optimierten Anordnung und Dimensionierung von Zeitzuschlägen im Eisenbahnbetrieb*, Universität Hannover, Eurailpress Tetzlaff-Hestra GmbH & Co., Hamburg, 2004
- [7] Tilli, J.S., *ATC on Danish railway lines*, Technical University of Denmark, 1991 (in Danish)
- [8] UIC leaflet 406, *Capacity*, 1st edition, UIC International Union of Railways, France, 2004
- [9] Vromans, M.J.C.M., Kroon, L.G., *Stochastic Optimization of Railway Timetables*, TRIAL Research School, Delft, 2004